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THESIS

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Radio Signals

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ABSTRACT

A well known problem associated with suppressed-carrier single sideband (SSB) communications is the difficulty of accurately tuning a receiver to the suppressed-carrier frequency of the transmitter if this frequency is not known a priori at the receiver. Although it is possible to tune a receiver to within 20 to 30 Hz of the correct frequency by tuning for the most natural voice timbre (in the case of radiotelephone voice transmissions), this is an unacceptably subjective and inexact method for use in signal and frequency monitoring applications.

This report describes an aural-visual method of tuning a SSB receiver to within about 3 Hz of the suppressed-carrier frequency of a SSB voice signal containing no discernable carrier. This tuning method supplements the familiar aural technique (tuning for most natural voice quality) with a visual oscilloscope display which facilitates an order of magnitude improvement in the accuracy of frequency measurement compared with aural tuning alone.

A theoretical analysis is presented which shows that SSB speech signals contain information sufficient to determine the suppressed-carrier frequency. Also described are experiments which were conducted to indicate the effectiveness of this tuning method in determining the carrier frequency of SSB signals when the SSB message is human speech.

It is suggested that this technique may find application in the domestic and international monitoring services.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

$d(t)$	Local-oscillator signal
$e(t)$	Output signal of an AM receiver
f_b	Beat frequency in Hz
f_d	$\omega_d/2\pi$ Hz
f_g	Frequency of signal generator in Hz
$f(t)$	An arbitrary function
$p(t)$	Output signal from product detector
$r(t)$	Single-sideband radio-frequency signal
$s(t)$	Simplified audio frequency message
t	Time in seconds
$v(t)$	Periodic approximation to a vowel tone
$E(t)$	Envelope of $r(t)$
T_f	Oscilloscope free running sweep period
T_o	Fundamental period of $v(t)$
T_t	Oscilloscope triggered sweep period
δ	Receiver tuning error in rad/sec
ω_c	Carrier frequency in rad/sec
ω_d	Frequency of the local oscillator signal in rad/sec
ω_o	Fundamental frequency of $v(t)$ and $s(t)$ in rad/sec

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I. INTRODUCTION

The principles and technical advantages of single-sideband (SSB) communications have been known and applied in the wired telephone and commercial point-to-point radiotelephone services for over fifty years. Only recently, however, has SSB come to be used for such applications as military tactical voice, long-range air-to-ground voice, amateur radiotelephone, ship-to-shore and ship-to-ship radiotelephone communications.

A well known difficulty associated with reception of suppressed-carrier single-sideband communication signals is the requirement for knowledge of the frequency and phase of the suppressed carrier to recover a replica of the modulating voltage. If maximum attainable carrier suppression is used, the SSB signal does not directly convey this knowledge of the frequency or phase of the carrier.

In point-to-point, common-carrier, fixed communication service, where the requirement exists to detect the transmitted waveform accurately, a pilot-carrier is usually transmitted to facilitate coherent demodulation of the SSB waveform [Ref. 1, p. 10]. In many other SSB applications, however, voice is the predominant modulating signal. Since the human ear is insensitive to phase distortion and is tolerant of small frequency errors, exact waveform reconstitution is not required and it is common practice in these applications to use maximum attainable carrier suppression.

A skilled radio operator, using his knowledge of what a human voice should sound like, can usually tune a SSB receiver to within 30 Hz of the correct frequency of a voice transmission by observing subtle

changes in voice quality which occur as the receiver tuning is adjusted [Ref. 1, p. 28; Ref. 2, p. 375]. This degree of accuracy is sufficient for most practical voice communication requirements, but it is considerably less than the desired degree of accuracy where a measurement of operating frequency or an analysis of signal characteristics is required.

There are more than 47 national administrations or international organizations which operate radio frequency-monitoring stations [Ref. 3, p. 2e]. In the high-frequency (HF) band of the radio spectrum (in which most SSB stations operate), international standards for monitoring accuracy have been established as ±5 parts in 10^6 below 4.0 MHz, and ±1.5 parts in 10^6 above 4.0 MHz [Ref. 2, p. 327]. SSB stations which do not transmit a residual carrier are particularly difficult to monitor since their signals have no identifiable characteristic frequency which can be measured directly [Ref. 2, p. 327 and 426]. If the modulation information is normal voice, an approximate measurement can be made by tuning a SSB receiver for minimum perceived distortion and measuring the frequency of the local oscillator; but since the expected error may be as large as 30 Hz this technique does not provide the monitoring accuracy specified.

What is needed is a means of measuring the suppressed-carrier frequency of SSB signals that provides about an order of magnitude improvement in accuracy. The equipment required should operate in real-time, should yield objective data that do not depend upon a value judgement by an operator, and should not be unduly complex or costly. Moreover, the method should be completely passive in that is should not rely on the station being monitored to send a standard tone or any other cooperative transmission.

In this report we present and describe a simple Aural-Visual Method (AVM)* for tuning a SSB receiver to within a few Hertz of the correct frequency of a SSB <u>voice</u> signal which contains no discernable carrier. This AVM requires a minimum of electronic equipment and enables an operator to tune a SSB receiver with an error as small as one-tenth that typically achieved by aural tuning alone.

Basic to the operation of the visual portion of this technique is the fact that a periodic time function (voltage) will appear stationary on an oscilloscope if it is synchronously displayed and will appear to drift slowly if it is displayed at a near-synchronous rate. In the visual phase of the AVM, the audio output (voltage vs time) of a SSB receiver is displayed on an oscilloscope which is triggered by a sampling function derived from envelope detection of the SSB signal. The operator first adjusts the receiver as accurately as possible by listening to the quality of the received speech (the aural phase). When the tuning error is small, he observes a characteristic lateral movement of the oscilloscope pattern which is directly related to tuning error. With further tuning of the receiver (the visual phase) he is then able to stop the net perceptible movement of the pattern. When the observed pattern is stationary the receiver is precisely tuned to the SSB signal.

This method of tuning is limited in application to SSB signals resulting from modulation by ordinary speech or, in special cases, modulation by multiple harmonic tones. The method does require a human operator to perform both aural and visual interpretations, but the

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*In this report, we sometimes use the term AVM to refer to our experimental operating <u>system</u> or any other operating system which implements this measurement and tuning technique.

operator does not require any particular technical knowledge and needs only elementary instruction to perform the necessary interpretation. Results are not instantaneous (one to five minutes of viewing time are needed typically for initial tuning) but the time required for tuning is such that the method can be used to track slowly drifting stations and can be used to perform on-the-air correction of stations that are off their assigned frequency. The AVM provides approximately an order of magnitude greater tuning accuracy than aural tuning alone, with consistent results showing less than ±3 Hz error.

A more detailed description of the AVM is presented in Chapter II. Chapter III contains a theoretical analysis of the principles basic to the AVM. The experimental apparatus and methods used in evaluating the performance of the AVM are discussed in Chapter IV as well as experimental results. Conclusions and recommendations for further study are contained in Chapter V. Four appendices contain supporting material. A list of references is provided.

II. DESCRIPTION OF THE AVM

A simplified system diagram of the AVM is shown in Fig. 1. Operation of the system is divided into two necessary and related steps.

The aural step is performed by an operator adjusting the frequency of the receiver local oscillator signal until the detected voice signal sounds as natural, intelligible and free of distortion as possible. This normally results in tuning to within ±30 Hz of the correct frequency.

The aural step is necessary because the visual fine tuning display will not yield useful information unless the receiver is tuned to very nearly the correct frequency. Also, if the aural information is disregarded, the receiver can be tuned to produce ambiguous solutions on the visual display. These false solutions usually occur when the tuning error is large, and they can be readily avoided by proper aural tuning.

To perform the visual tuning step the audio output from the SSB receiver is displayed as a function of time on a general-purpose oscilloscope. The triggering signal which initiates each trace is obtained from the audio (detected envelope) output of a commercial AM receiver tuned to the SSB signal. As explained in Chapter III, such triggering has the effect of synchronously sampling the displayed waveform when the SSB receiver is correctly tuned.

The visual step consists of the operator observing the display while slowly tuning through the narrow band of aurally acceptable frequencies. As correct tuning is approached, the operator sees a characteristic pattern similar to that of Fig. 2a. The sequence of the individual traces in the display is such, however, that when

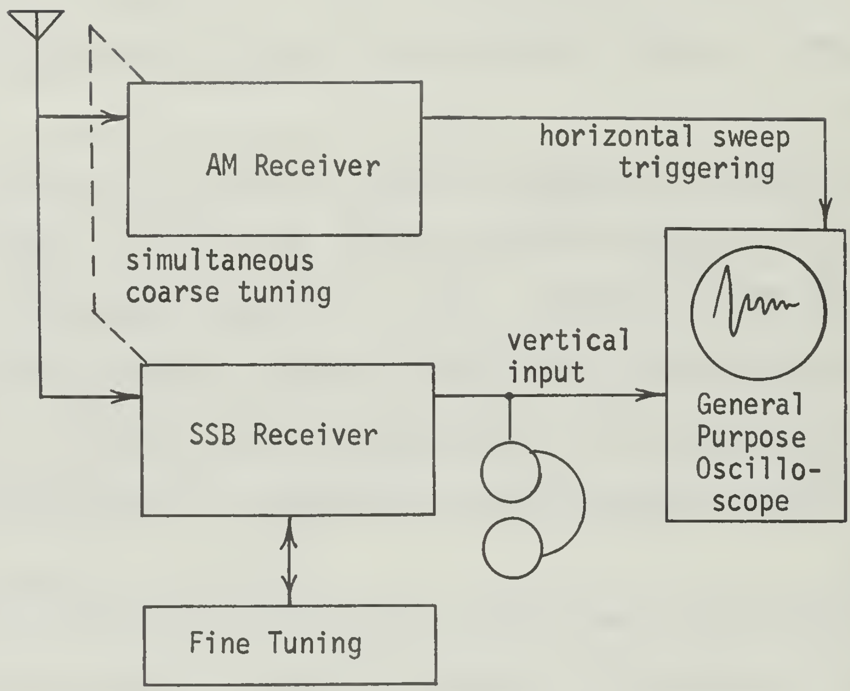
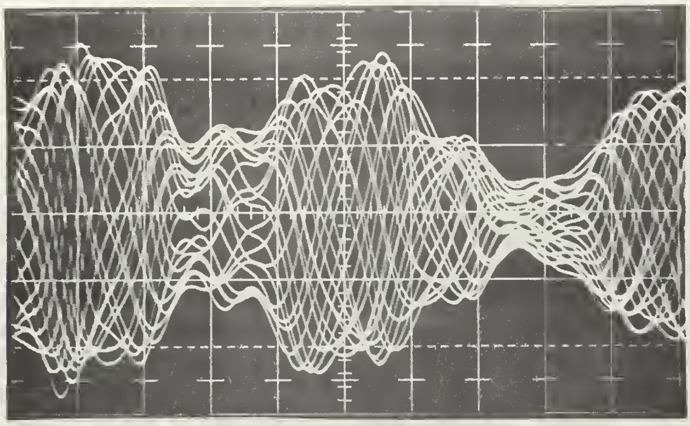
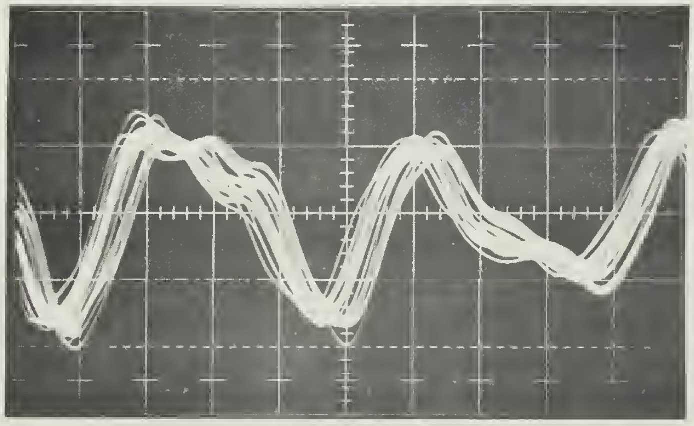


FIG. 1. SIMPLIFIED SYSTEM DIAGRAM OF THE AVM



a. Receiver frequency differs from transmitter frequency by approximately 5.0 Hz.



b. Receiver frequency tuned to within 0.5 Hz of transmitter suppressed carrier frequency.

FIG. 2. TYPICAL AVM VISUAL DISPLAY. Approximately one second exposure photograph during an extended speech vowel sound.

viewed continuously, the pattern is suggestive of waves moving either to the left or to the right. We indicate in Chapter III that the occurrence of these moving waves coincides with the presence of strong quasi-periodic* vowel sounds in the SSB detected speech signal.

Fine-tuning is completed by adjusting the frequency of the receiver local oscillator signal to stop the apparent lateral movement of the pattern. When the receiver is correctly tuned, the quasi-periodic waveform of long vowel sounds will repeatedly overtrace the same basic pattern for many sweeps as shown in Fig. 2b.

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*For purposes of this paper a quasi-periodic function is defined as a function which is repeated, approximately, over several successive approximately equal intervals of time. Fig. 2b is a typical example of several cycles of a quasi-periodic function. [Ref. 4, p. 57]

III. ANALYTICAL RESULTS

Since it is not possible to write an analytic expression for human speech, it is not possible to analyze the AVM with mathematical precision in terms of the signal with which it is intended to operate. However, it is possible to write an expression which approximates a sample of speech. Therefore, analysis will proceed in terms of a function which conveniently approximates a human speech vowel sound.

A. PERIODIC ANALYSIS

1. The Periodic Message Function

Speech has been described, in its simplest terms, as a modulation process in which a "carrier" is modulated in several ways to convey information [Ref. 1, p. 323]. This "carrier", in the case of voiced vowel sounds, consists of a fundamental vocal-cord tone and a broad spectrum of harmonics of this fundamental [Ref. 5, p. 35-24]. The average fundamental frequency is about 130 Hz for male adults and about 205 Hz for females.

In Section B of this chapter it is shown that experimental evidence supports the conclusion that voiced vowel sounds may be reasonably approximated by a sum of sinusoidal terms of the form

$$v(t) = a_1 \cos(\omega_o t) + a_2 \cos(2\omega_o t) + \ldots + a_n \cos(n\omega_o t) \qquad (1)$$

where ω_o is the fundamental frequency in rad/sec and the coefficients a_1, a_2, etc. are constants.

If a signal voltage described by $v(t)$ in Eq. (1) is passed through an ideal amplifier having a 300 Hz to 3000 Hz bandpass associated with a speech communication system, all terms with frequencies

less than 300 Hz or greater than 3000 Hz will not appear at the amplifier output. The description of this filtered voltage is still a rather unwieldy function, however, because of the number of terms present. Therefore, we will arbitrarily choose coefficients for the expression in Eq. (1) to form a periodic message function $s(t)$ such that

$$s(t) = \cos(3\omega_o t) + \cos(4\omega_o t) + \ldots + \cos(7\omega_o t) , \tag{2}$$

where ω_o is such that $3\omega_o > 300$ Hz and $7\omega_o < 3000$ Hz.

Analysis of the AVM visual display will be in terms of this periodic message function $s(t)$. We consider first the modulation process and then in sections 3 and 4 the demodulation process involving this message function.

2. SSB Modulation by the Message Function

If an audio frequency voltage described by Eq. (2) is used to SSB modulate a carrier of frequency ω_c the resulting upper sideband is a signal $r(t)$ which can be written as a sum of sinusoidal terms

$$r(t) = \cos(3\omega_o + \omega_c)t + \cos(4\omega_o + \omega_c)t + \ldots + \cos(7\omega_o + \omega_c)t . \tag{3}$$

Using trigonometric substitution, this expression may also be written as

$$r(t) = 2 \left[\frac{1}{2} + \cos(\omega_o t) + \cos(2\omega_o t) \right] \cos(5\omega_o + \omega_c)t . \tag{4}$$

If we let

$$E(t) = 2 \left[\frac{1}{2} + \cos(\omega_o t) + \cos(2\omega_o t) \right] \tag{5}$$

then

$$r(t) = E(t) \cos(5\omega_o + \omega_c)t \tag{6}$$

is recognized as being of the form of the product of an envelope

function $E(t)$ and a carrier function $\cos(5\omega_o + \omega_c)t$. This carrier function does not describe the carrier which was suppressed in the SSB modulation process. And the envelope function $E(t)$ is not equivalent to the message function $s(t)$, but there is a unique relationship between $E(t)$ and $s(t)$ which is developed in Section 4 of this chapter.

We will consider first product detection and then envelope detection of $s(t)$.

3. Product Detection of the SSB Signal

To recover the message function $s(t)$, product detection is used where the product of $r(t)$ and a detection function (local oscillator signal)

$$d(t) = 2 \cos(\omega_d t) \tag{7}$$

is formed and lowpass filtered to form $p(t)$ which may be expressed as

$$p(t) = \cos(3\omega_o + \omega_c - \omega_d)t + \cos(4\omega_o + \omega_c - \omega_d)t + \ldots$$
$$+ \cos(7\omega_o + \omega_c - \omega_d)t. \tag{8}$$

For coherent detection $d(t)$ should have precisely the same frequency and phase as the suppressed carrier. If $\omega_d = \omega_c$ in Eq. (8), the detected signal $p(t)$ becomes the message function $s(t)$ of Eq. (2).

Since ω_c is not usually known exactly at the receiver, there will generally be a frequency error δ where

$$\delta = \omega_d - \omega_c . \tag{9}$$

If $\delta \neq 0$, Eq. (8) may be written

$$p(t) = \cos(3\omega_o - \delta)t + \cos(4\omega_o - \delta)t + \ldots + \cos(7\omega_o - \delta)t . \tag{10}$$

A result of importance here is seen by comparing Eq. (2) with Eq. (10). Each term of Eq. (2) represents a harmonic of the fundamental ω_o for any value of ω_o. In Eq. (10), the terms are harmonically related for all values of ω_o only if $\delta = 0$. The significance of this is the known result that SSB mistuning does not simply alter the pitch of a group of harmonic tones, it also alters the harmonic relationship [Ref. 1, p. 28].

4. Envelope Detection of the SSB Signal

Since the envelope of a SSB signal is not linearly related to the modulating function (compare Eq. (4) with Eq. (2)), envelope detection of a SSB signal is usually of little interest. The output of an envelope detector does, however, contain information about the modulating function which is not readily obtainable from the product detected signal. This is seen by recalling that in Eq. (4), $r(t)$ is written as the product of an envelope function and a carrier function. The envelope function

$$E(t) = 2 \left[\frac{1}{2} + \cos(\omega_o t) + \cos(2\omega_o t) \right] \qquad (5)$$

is not equivalent to the message function $s(t)$, but it is periodic with the same period as $s(t)$. This result is used in the AVM to obtain a reference signal for receiver tuning.

Envelope detection of $r(t)$ is mathematically equivalent to forming the absolute value of $E(t)$. The result is obtainable by inspection when the constant term in $E(t)$ is large enough so that $E(t)$ is always greater than zero. If this condition does not exist, the analytic expression for the envelope detected signal is more involved. An exact expression, however, is not needed for our purpose.

It can be reasoned inductively that if $v(t)$ of Eq. (1) is periodic with a period T_0 where

$$T_0 = \frac{2\pi}{\omega_0} \tag{11}$$

$s(t)$ and $E(t)$ are both periodic with the same period. Further, if $E(t)$ is periodic with period T_0, then $|E(t)|$ is also periodic with the same period. ($|E(t)|$ is the absolute value of $E(t)$.) $|E(t)|$ in general contains a DC term which disappears in normal audio frequency amplification, and so we define an ac voltage $e(t)$ which is the audio frequency output of an AM receiver tuned to the SSB signal, $r(t)$.

The function $e(t)$ is not, in general, an intelligible replica of either the voice approximation $v(t)$ or the simplified periodic message function $s(t)$. Of importance is the result that $e(t)$ is periodic with the same period as $v(t)$ and $s(t)$. This audio signal $e(t)$ has a complex harmonic structure which is different from that of $s(t)$, but the harmonics of $e(t)$ are harmonics of the same fundamental frequency present in $s(t)$. Since the envelope detection process is independent of the local-oscillator signal frequency ω_d , the harmonic structure of $e(t)$ is not affected by fine-tuning error of the receiver [Ref. 6, p. 4]. The function $e(t)$, then, is used in the AVM system as an independent source of a reference signal to obtain synchronous tuning of the SSB receiver, as illustrated in Fig. 3 and described in the next part of this chapter.

5. Aural-Visual Tuning Using a Multi-Tone Signal

Suppose that the envelope-detected signal $e(t)$ is used to trigger the horizontal sweep of a cathode-ray oscilloscope. Assume the

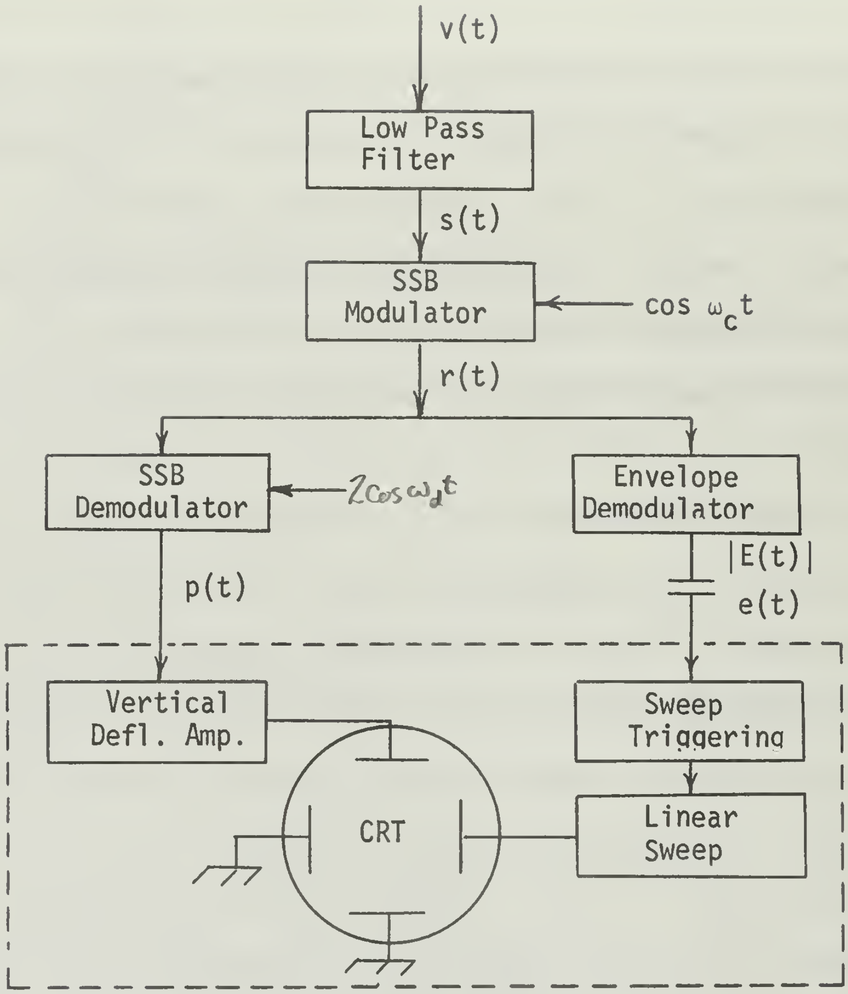


FIG. 3. DIAGRAM OF SIGNALS IN THE AVM.

sweep period is adjusted so that the oscilloscope free-running sweep period T_f is slightly less than T_o, the period of $e(t)$. That is,

$$T_f = T_o - \varepsilon \quad , \quad \text{where} \quad \varepsilon << T_o \; . \tag{12}$$

It will be possible, then, to trigger the sweep from some unique point on the waveform of $e(t)$ such that a new trace will be initiated by each successive cycle of $e(t)$ and the triggered sweep repetition period will be T_t where

$$T_t = T_o = \frac{2\pi}{\omega_o} \; . \tag{13}$$

Recall that T_o is unaffected by receiver tuning. This means that the oscilloscope is triggered at a constant rate (every T_o seconds) independent of receiver tuning. As an example, if a voltage

$$f_1(t) = \cos(2\omega_o t) \tag{14}$$

is now applied to the vertical input of the oscilloscope, the trace will appear stationary because a new trace will be initiated each 4π radians of phase of $f_1(t)$ and each new trace will overlay or retrace the previous one.

Suppose, on the other hand, that a voltage

$$f_2(t) = \cos(2\omega_o - \delta)t \tag{15}$$

is displayed. In this case $f_2(t)$ will undergo $4\pi - \frac{2\pi\delta}{\omega_o}$ radians of phase change during a triggered sweep period T_f. If $\delta < 0$ (frequency of $f_2(t)$ <u>greater</u> than that of $f_1(t)$) each successive trace of $f_2(t)$ will begin with a phase angle increased by $\frac{2\pi\delta}{\omega_o}$ radians relative to

that of the previous trace with the result that the waveform will give the appearance or illusion of moving from right to left on the screen. Similarly, when $\delta > 0$ the display will appear to move from left to right. This process is shown graphically by Fig. 4 where, for ease of construction and interpretation, a triangular wave is shown instead of a sine wave.

There are two ways then to explain the nature of the visual display when the product detected signal $p(t)$ is displayed on an oscilloscope that is triggered by the envelope detected signal $e(t)$ at a rate that is a harmonic or sub-harmonic of ω_o. The first way is to regard $p(t)$ as a sum of sinusoidal terms as in Eq. (10) with the interpretation that each of these sinusoids will appear to move at a rate of $\frac{2\pi\delta}{\omega_o}$ radians per sweep. The objection to this description is that the appearance of the signal described by Eq. (10) is not entirely obvious from this form of the equation.

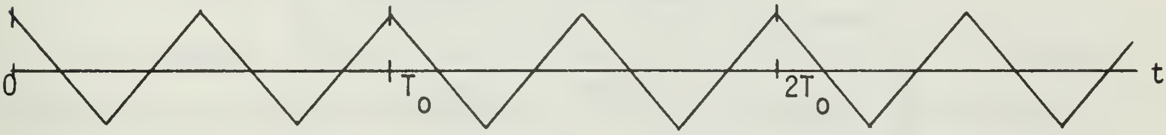
It is more instructive to put $p(t)$ into the form of Eq. (4) so that

$$p(t) = 2\left[\frac{1}{2} + \cos(\omega_o t) + \cos(2\omega_o t)\right]\cos(5\omega_o - \delta)t . \qquad (16)$$

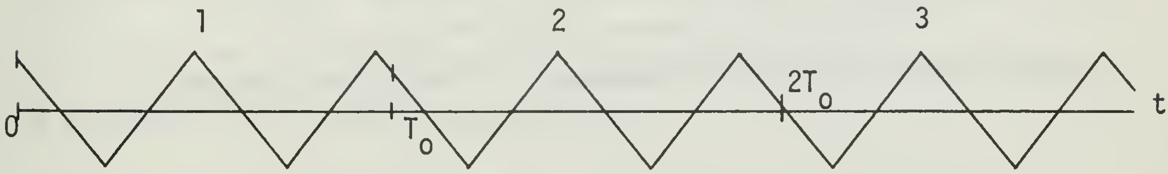
In this form only the argument of the carrier term contains a dependence upon δ. The envelope term, in square brackets, is a function of ω_o and will appear as a stationary amplitude constraint upon the carrier sinusoid as the carrier sinusoid appears to move at a rate of $\frac{2\pi\delta}{\omega_o}$ radians per sweep. The significance here of the stationary envelope concept is in the explanation which this provides for the experimental results shown by Fig. 14h in the next Chapter.

The sign of δ is chosen, in Eq. (9), such that for $\delta > 0$, the movement is to the right for an upper-sideband signal. An analysis

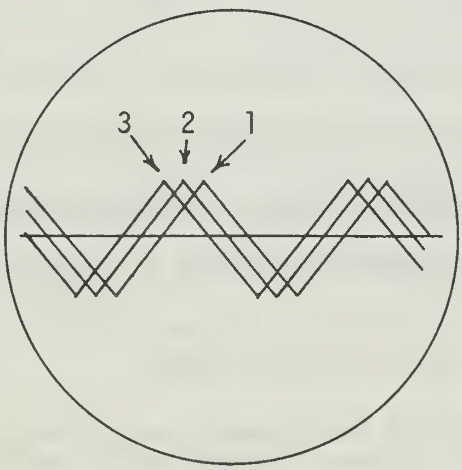
a. Trigger waveform.



b. Second harmonic of trigger waveform.



c. Higher frequency version of the waveform of b.



d. Oscilloscope presentation
of the waveform of c.

FIG. 4. CONSTRUCTION SHOWING LATERAL MOVEMENT
OF THE OSCILLOSCOPE PRESENTATION.

for lower-sideband signals yields an opposite result. Tabulation of the relationships of tuning error, sideband and apparent movment are shown in Fig. 5.

DIRECTION OF PATTERN MOVEMENT		
Tuning Error	Upper Sideband Transmission	Lower Sideband Transmission
$\delta > 0$	→	←
$\delta = 0$	Stationary	Stationary
$\delta < 0$	←	→

Tuning Error = (Receiver Frequency) - (Transmitter Frequency)

FIG. 5. TABULATION OF THE DIRECTION OF THE LATERAL MOVEMENT OF THE OSCILLOSCOPE DISPLAY.

In the next section, these results obtained using a periodic message function are applied to speech signals by presenting experimental evidence of the harmonic structure of vowel sounds.

B. APPLICATION OF THE AVM TO SPEECH SIGNALS

The previous theoretical development considered a message function which was composed of two or more harmonic components and which was strictly periodic. To apply this development to speech signals, it is necessary to show that, at least over finite intervals of significance, a speech signal appears to have a harmonic spectrum and hence can be considered to be a quasi-periodic waveform.

Five examples of typical sustained vowel sounds recorded from the output of a synchronously tuned SSB receiver are shown in Figs. 6 through 10. The upper representation in each figure is the voltage vs time waveform of the particular sound. The lower representation is a sound spectrogram — often called a sonogram — of the same vowel sound but not necessarily the same identical sample.

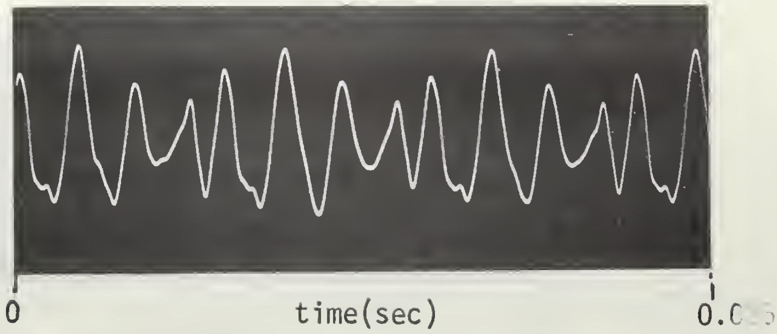
The sonogram represents time along the horizontal axis, frequency along the vertical axis and spectral density in degree of blackness. The first one-half inch or so of each plot shows the spectrum of a narrow 240 Hz pulse. This is included to provide an approximate frequency calibration for each plot. The remainder of each spectrogram is devoted to the vowel sound spectrum.

A careful examination of each of the voltage waveforms reveals approximately three cycles of a repetitive form. Successive cycles of each waveform are almost identical and have almost the same period.

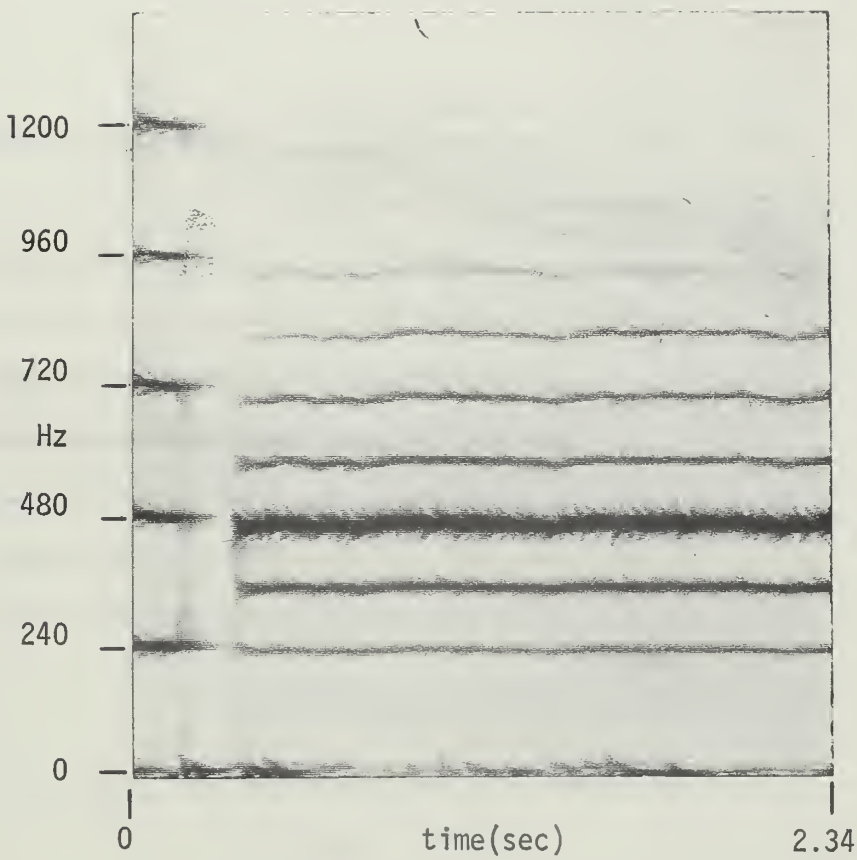
Examination of each spectrum reveals that essentially all the energy present is distributed into distinct frequency lines each of which appears to be a harmonic of a common fundamental. The fundamental frequency in these examples is either very faint or totally absent as a result of the bandpass characteristics of both the SSB transmitter and SSB receiver.

We conclude from these experimental examples, then, that vowel sounds are quasi-periodic and have harmonic spectra [Ref. 1, p. 323; Ref. 4, p. 57; Ref. 5, p. 35-24]. From this we infer that the previous analysis of the AVM using a periodic function predicts to a good approximation the response of the AVM system to a sustained vowel sound.

To go a step further, it is also instructive to observe a spectrogram of normal speech to see whether the vowel sound harmonics become obscured by noise or are of such short duration as to be unrecognizable in context. Fig. 10 is a spectrogram of a rather long word. It shows a variety of speech sounds, including noisy sibilant sounds, but the harmonic structure is evident and the concentration of energy is primarily in the harmonic sounds. It therefore appears reasonable to conclude that the AVM will function as predicted by the analysis of Section A of this Chapter when the modulating signal is human speech.

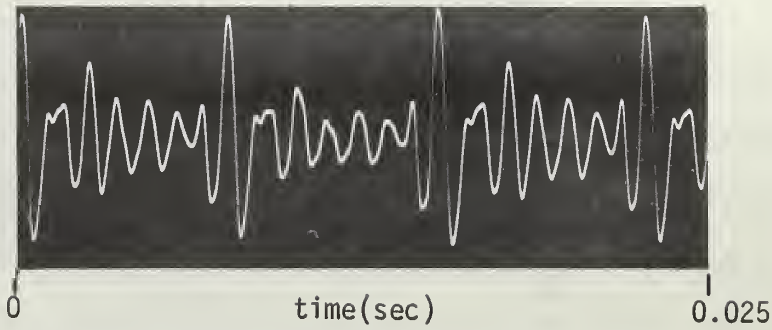


a. Voltage vs time waveform

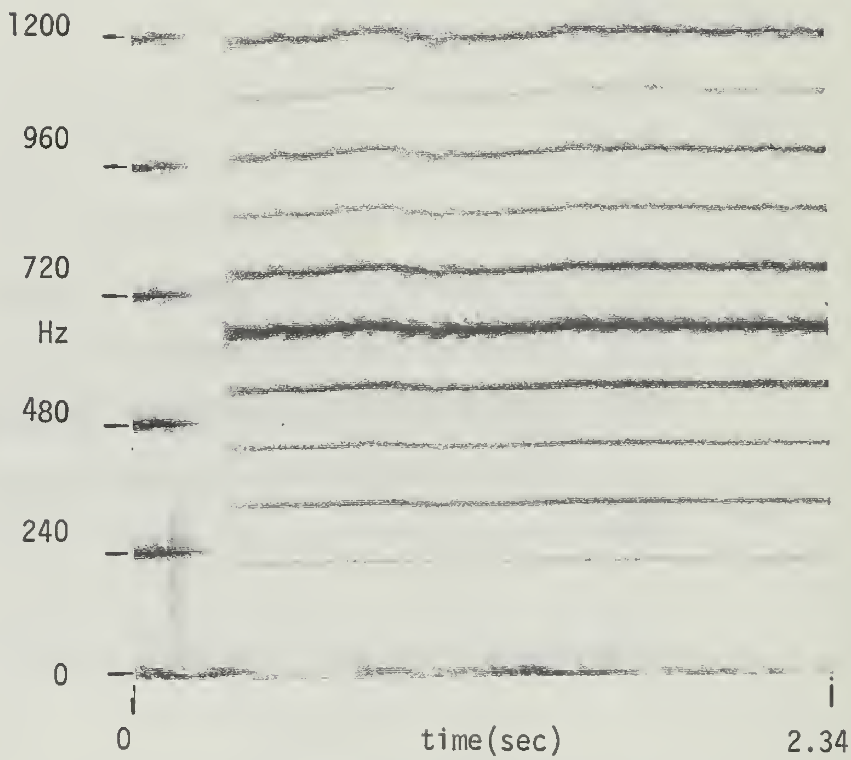


b. Spectrogram of the waveform of a.

FIG. 6. TIME WAVEFORM AND SOUND SPECTROGRAM OF SUSTAINED SPEECH VOWEL SOUND: LONG ō AS IN "JŌE".

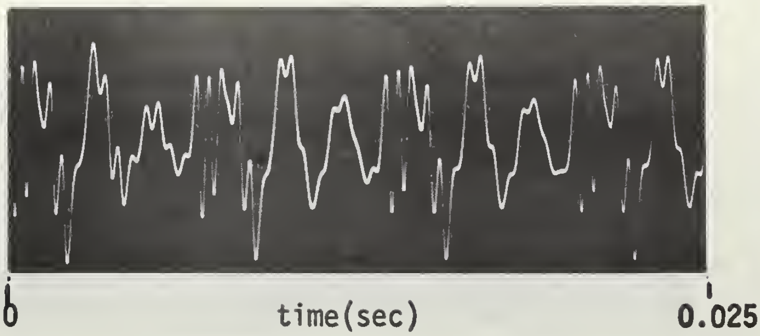


a. Voltage vs time waveform.

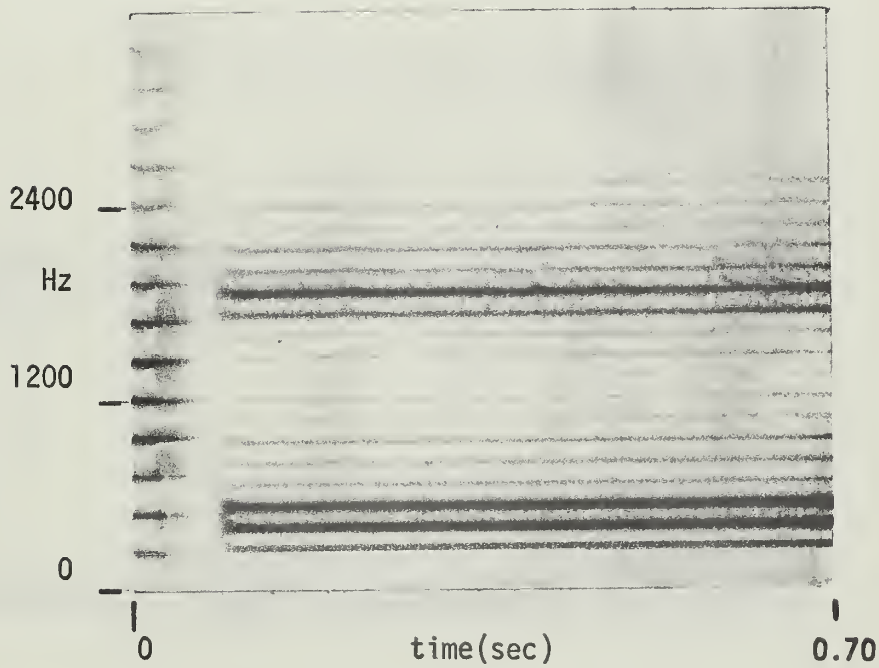


b. Spectrogram of the waveform of a.

FIG. 7. TIME WAVEFORM AND SOUND SPECTROGRAM OF SUSTAINED SPEECH VOWEL SOUND: a AS IN "FATHER".

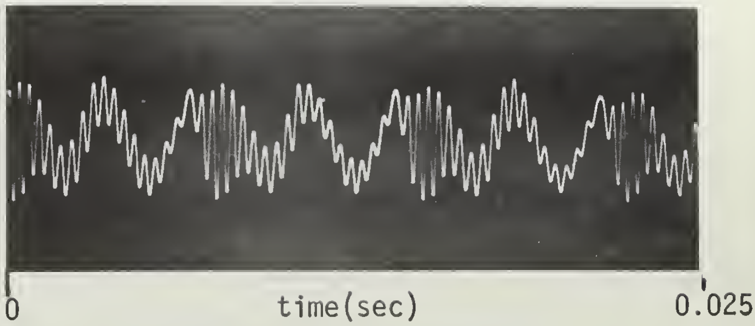


a. Voltage vs time waveform.

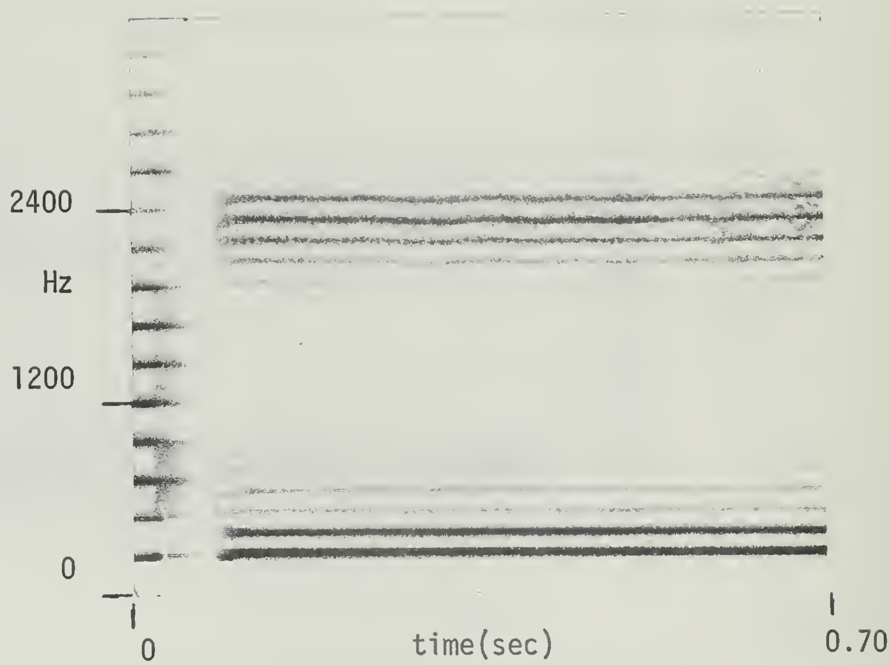


b. Spectrogram of the waveform of a.

FIG. 8. TIME WAVEFORM AND SOUND SPECTROGRAM OF SUSTAINED SPEECH VOWEL SOUND: LONG ā AS IN "HĀTE".

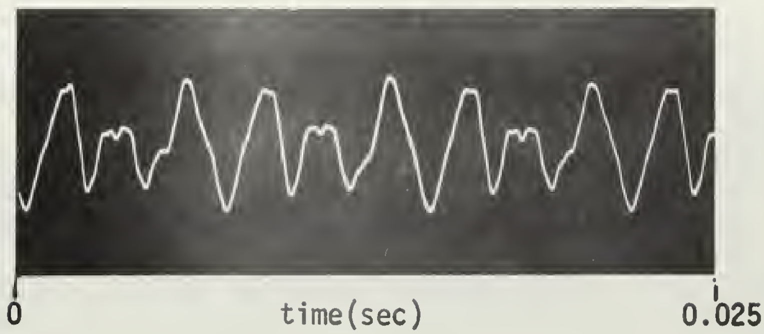


a. Voltage vs time waveform.

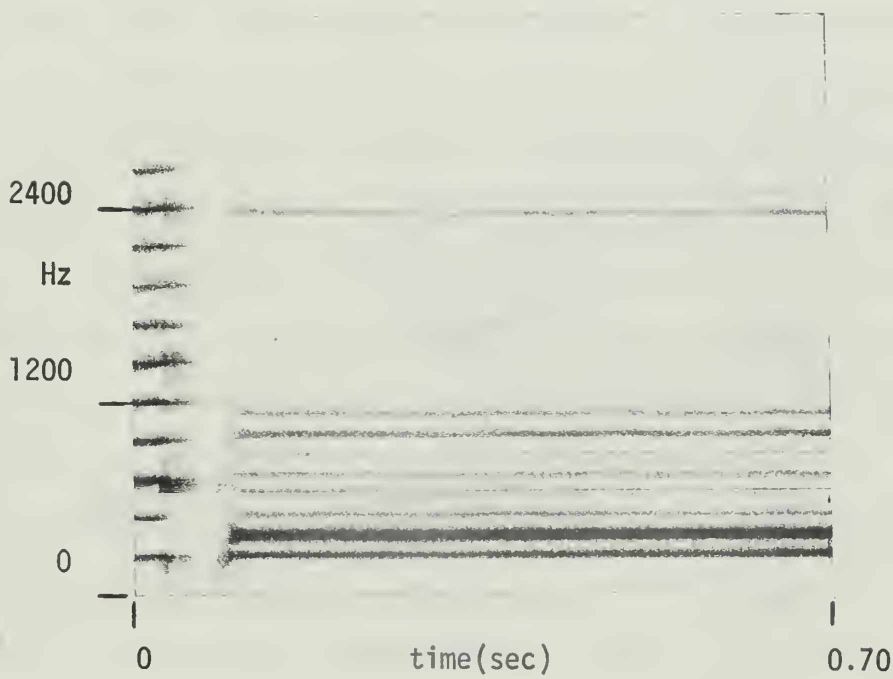


b. Spectrogram of the waveform of a.

FIG. 9. TIME WAVEFORM AND SOUND SPECTROGRAM OF SUSTAINED SPEECH VOWEL SOUND: LONG ē AS IN "BĒ".



a. Voltage vs time waveform.



b. Spectrogram of the waveform of a.

FIG. 10. TIME WAVEFORM AND SOUND SPECTROGRAM OF SUSTAINED SPEECH VOWEL SOUND: LONG $\bar{u}$ OR $\overline{oo}$ AS IN "R$\bar{U}$DE" OR "M$\overline{OO}$N".

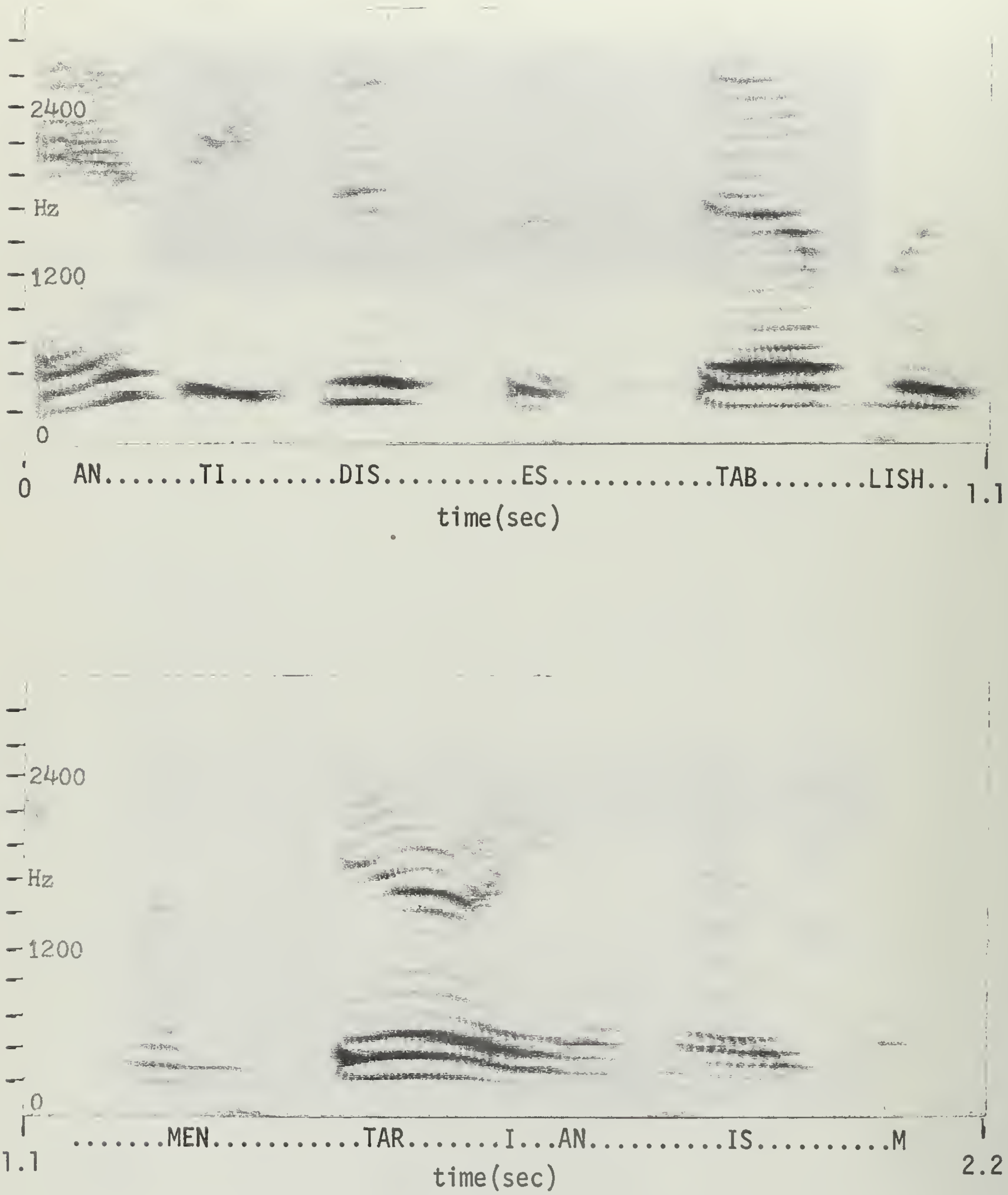


FIG. 11. SOUND SPECTROGRAM OF A LONG WORD: "ANTIDISESTABLISHMENTARIANISM".

IV. EXPERIMENTAL RESULTS

A. EXPERIMENTAL APPARATUS

A block diagram of the basic experimental apparatus used to verify the operation of the AVM is shown in Fig. 12. The equipment is used in two fundamentally different configurations; the closed-circuit SSB (CCSSB) configuration and the on-the-air configuration. The closed circuit mode is used for laboratory measurements where the relative frequency error of the transmitter and the receiver is precisely controlled. The on-the-air mode is used for measurements of typical "live" SSB signals.

1. The SSB Receiver

A basic unit of the experimental apparatus is an R-1051-B/URR receiver. This receiver employs digital tuning to derive incrementally any one of 280,000 frequencies ending in a multiple of 100 Hz between 2.0 MHz and 30.0 MHz. Optional vernier tuning is also provided for continuous coverage throughout the frequency range [Ref. 6, p. 4-2].

When incremental tuning is used, all of the frequency determining oscillators are related to a precise (stability of 1 part in 10^8 per day) 5 MHz internal standard by either phase-lock or drift-cancellation methods. This results in receiver tuning that is coherent with the phase of the internal standard.

When vernier tuning is used, one oscillator is unlocked from the standard and is voltage tuned to provide continuous interpolation between each 1.0 kHz dial increment. In this mode phase lock is not maintained, but the overall receiver frequency may be calculated to within one Hz by measuring the frequency of the vernier oscillator.

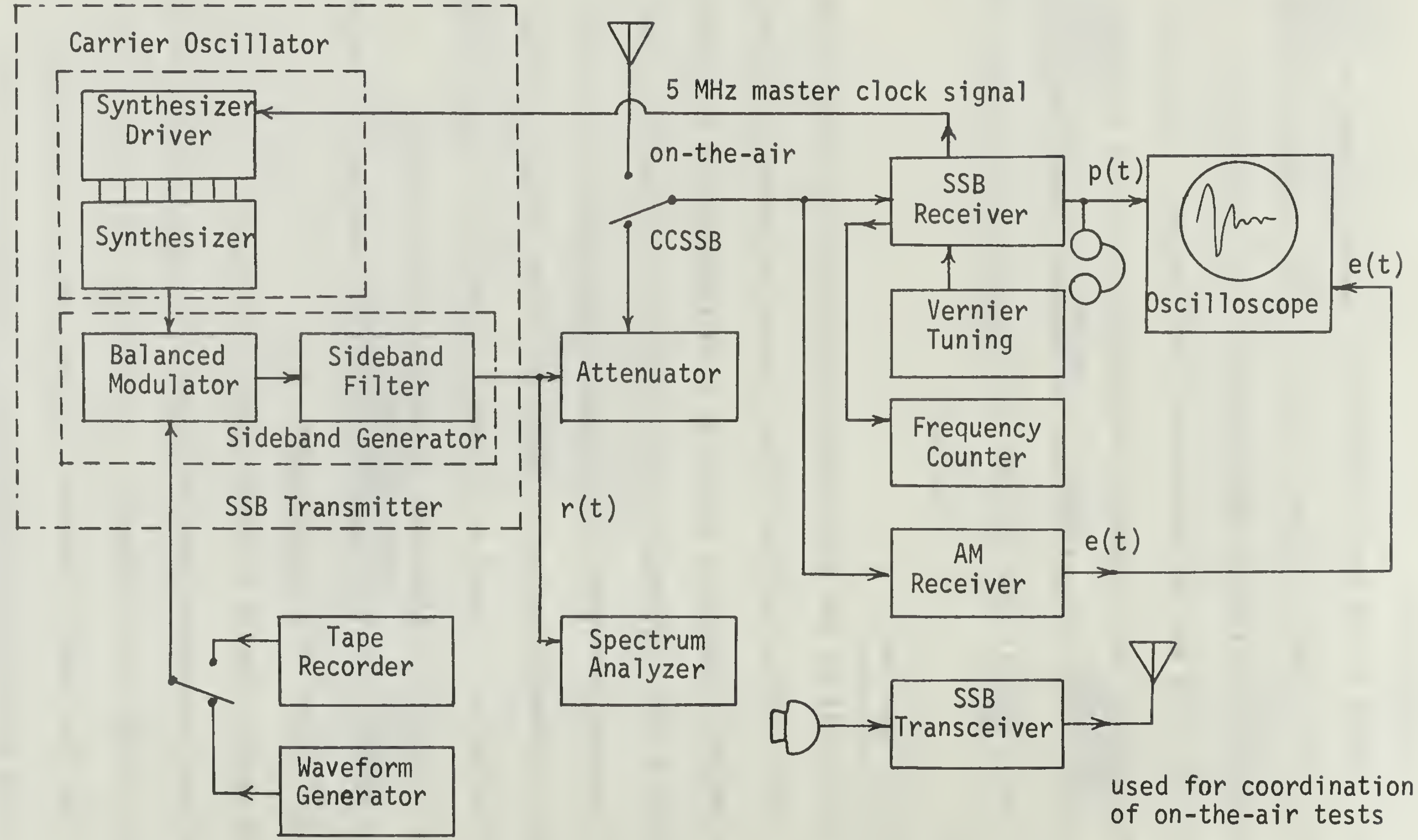


FIG. 12. BLOCK DIAGRAM OF THE EXPERIMENTAL SSB SYSTEM.

To facilitate precise tuning in the vernier mode an external vernier control with a resolution of about 1/3 Hz frequency change per degree of dial rotation is connected to the receiver. This is used in conjunction with a digital frequency counter connected in such a manner that the three least significant figures of the receiver operating frequency may be read directly from the counter. Details of the counter and vernier accessories are described in Appendix A.

When the system is used in the closed-circuit configuration, incremental receiver tuning may be used with the 5 MHz standard in the receiver serving as the master clock for the system. In this mode the receiver is normally tuned to precisely 8998.400 kHz.

2. The SSB Transmitter

The SSB "transmitter" used for closed-circuit operation consists of a very precise frequency synthesizer (used for the carrier oscillator), a solid-state double balanced modulator and a 9.0 MHz crystal sideband filter. Details of the modulator and filter are contained in Appendix B.

The synthesizer used for the carrier oscillator is actually two units, an HP-5105A Frequency Synthesizer and an HP-5110B Synthesizer Driver. The Synthesizer Driver is synchronized to the 5 MHz signal from the receiver standard to provide coherence between the receiver and the transmitter.

The synthesizer frequency may be changed in coherent increments of 0.1 Hz. Since this is ten times finer resolution than is obtainable with receiver tuning, the receiver may be fixed tuned and very small tuning errors simulated by varying the transmitter frequency in 0.1 Hz increments about the nominal suppressed-carrier frequency of 8998.4000 kHz.

3. The AM Receiver

Although the envelope detected reference signal e(t) could be readily obtained by rectifying a sample of the intermediate frequency (IF) signal in the SSB receiver, a separate receiver is used for convenience and flexibility.

Since the time constants of the usual diode detector and AVC circuit found in an AM receiver are not usually designed to follow the envelope of a SSB signal, a certain amount of distortion is introduced by an AM receiver used in this manner.

Both an R-1051-B/URR and a Hallicrafters SX-130 were used as AM receivers. Either receiver provides satisfactory reference signals but the SX-130 follows the envelope of the SSB signal with less distortion.

4. Other Equipment

The oscilloscope used for these experiments is a general purpose laboratory unit with provision for external sweep triggering and a one-sweep feature (Tektronix 544) used to make photographs.

An RF Spectrum Analyzer (TS 1379 A/U) was used to monitor the transmitter output to ensure adequate carrier suppression, unwanted sideband suppression and the absence of in-band spurious responses.

Two sources of audio frequency signals are shown in Fig. 12.

A tape recorder is used for voice signals and a Barber Laboratories Complex-Wave Generator is used to provide simple harmonic signals. For coordination of tests with "live" SSB stations, a URC-32B transceiver was used to provide two-way communications.

B. AURAL-VISUAL DISPLAY OF A TWO-TONE MESSAGE FUNCTION

The first signal chosen to demonstrate the behavior of the AVM is the voltage waveform shown in Fig. 14a. This is formed with a complex wave generator that adds a 1500 Hz third harmonic sinusoid voltage to a 500 Hz fundamental sinusoid. The signal may be described as

$$s_1(t) = \cos 2\pi(500)t - \cos [2\pi(1500)t] \; . \tag{17}$$

If this voltage is used to modulate the closed-circuit SSB transmitter, the audio frequency output of the SSB receiver will be of the form

$$p_1(t) = \cos [2\pi(500) - \delta]t - \cos [2\pi(1500) - \delta]t \tag{18}$$

$$p_1(t) = p_{11}(t) + p_{12}(t) \tag{19}$$

where δ is defined by Eq. (9) and the individual terms are identified as

$$p_{11}(t) = \cos [2\pi(500 - \delta)]t \tag{20}$$

and

$$p_{12}(t) = - \cos [2\pi(1500) - \delta]t \; . \tag{21}$$

A more useful form of $p_1(t)$ is obtained by rewriting Eq. (18) using trigonometric relations to obtain

$$p_1(t) = 2 \sin [2\pi(500)t] \cdot \sin [2\pi(1000) - \delta]t \tag{22}$$

$$= E_1(t) \sin [2\pi(1000) - \delta]t \tag{23}$$

where

$$E_1(t) = 2 \sin [2\pi(500)t] \; . \tag{24}$$

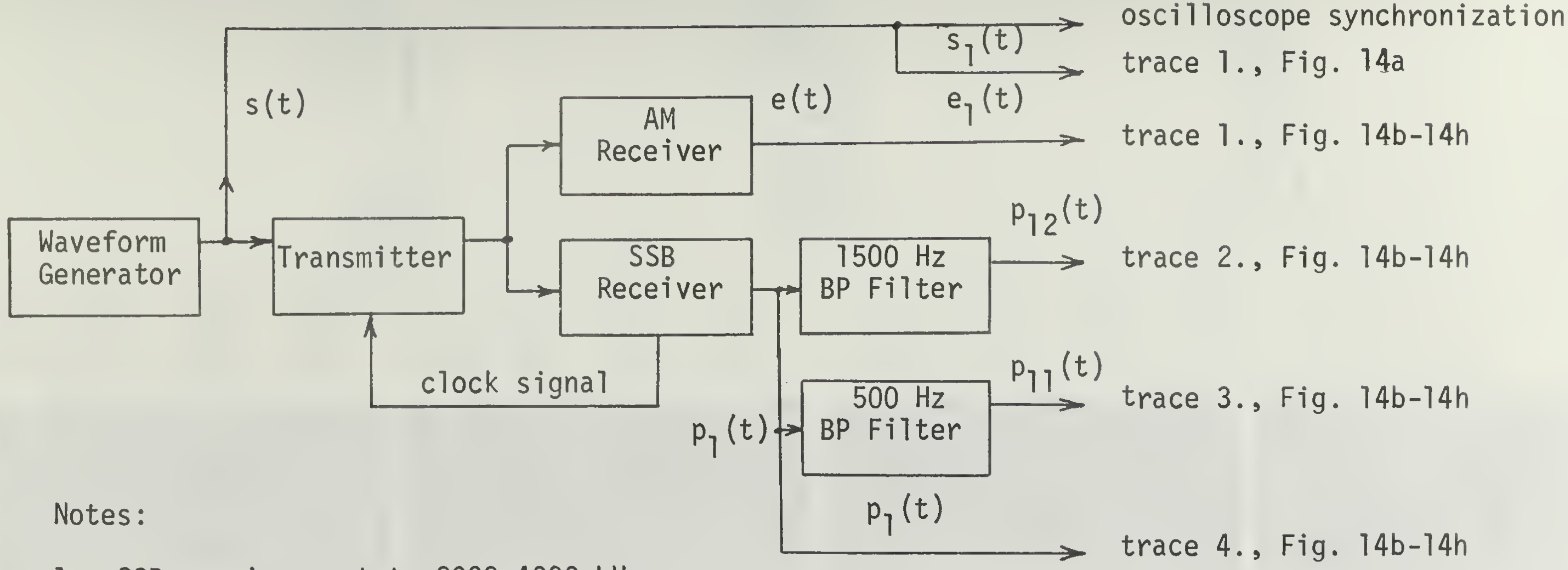
The response of the experimental system to the signal described by Eq. (17) is shown in Fig. 14. These photographs were made using two bandpass filters and a four trace oscilloscope preamplifier connected as shown in Fig. 13.

The audio frequency modulating voltage is shown in Fig. 14a. In each of the succeeding photographs, Fig. 14b through Fig. 14h, the upper trace is the envelope detected reference signal $e_1(t)$. The next trace is the 1500 Hz component of the product detected signal $p_{12}(t)$. The third trace from the top is the 500 Hz component $p_{11}(t)$. And the lower trace is the product-detected audio frequency signal $p_1(t)$ at the output of the SSB receiver.

Fig. 14b is the visual display obtained when the transmitter and receiver are synchronized $(\delta = 0)$ and the phase difference between the transmitter and receiver has been adjusted to receive the two harmonic components in approximately the same phase as they were transmitted.

When the transmitter frequency is increased by 0.1 Hz (to 8998.4001 kHz) the lower three traces move to the left at a rate of 0.2π radians per second, as predicted, and the reference signal (top trace) remains stationary. This is shown qualitatively in Figs. 14g and 14h. Fig. 14g is a sequential multiple exposure photograph showing the initial movement of the pattern. Fig. 14h is a time exposure which allows the pattern to drift through a full cycle of movement.

A more detailed study can be made from Figs. 14b - 14f which show the progress of the waveform as it drifts through a half-cycle of change in increments of $\pi/4$ radians. The motion of each waveform can be seen from the displacement of the reference points which are indicated by white arrowheads.



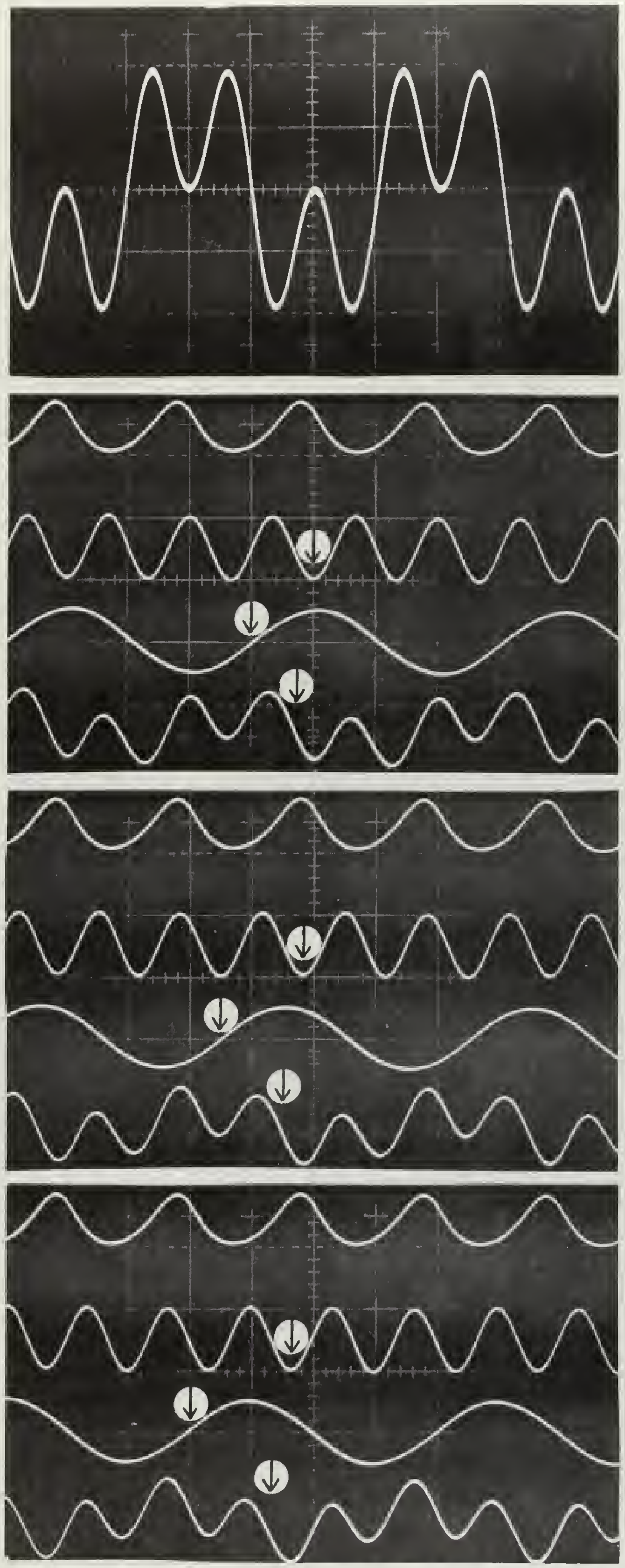
Notes:

1. SSB receiver set to 8998.4000 kHz.

2. Transmitter set to 8998.4001 kHz.

3. Oscilloscope triggered from waveform generator to verify stationarity of the $e(t)$ trace with respect to the input (modulating) function.

FIG. 13. BLOCK DIAGRAM OF THE SYSTEM USED TO OBTAIN THE PHOTOGRAPHS OF FIG. 14.



a. The periodic message function $s_1(t)$.

b. AVM signals
Phase = 0 rad
δ = 0.0 Hz

$e_1(t)$

$p_{12}(t)$

$p_{11}(t)$

$p_1(t)$

c. AVM signals
Phase = $-\pi/4$ rad
δ = -0.1 Hz

$e_1(t)$

$p_{12}(t)$

$p_{11}(t)$

$p_1(t)$

d. AVM signals
Phase = $-\pi/2$ rad
δ = -0.1 Hz

$e_1(t)$

$p_{12}(t)$

$p_{11}(t)$

$p_1(t)$

FIG. 14. OSCILLOGRAMS SHOWING SYSTEM RESPONSE TO A TWO-TONE HARMONIC SIGNAL.

e. AVM signals
Phase = $-3\pi/4$ rad
δ = -0.1 Hz

$e_1(t)$
$p_{12}(t)$
$p_{11}(t)$
$p_1(t)$

f. AVM signals
Phase = $-\pi$ rad
δ = -0.1 Hz

$e_1(t)$
$p_{12}(t)$
$p_{11}(t)$
$p_1(t)$

g. Sequential multiple exposure showing relative movement.

$e_1(t)$
$p_{12}(t)$
$p_{11}(t)$
$p_1(t)$

h. Time exposure showing movement through a complete 2π radians of phase change.

$e_1(t)$
$p_{12}(t)$
$p_{11}(t)$
$p_1(t)$

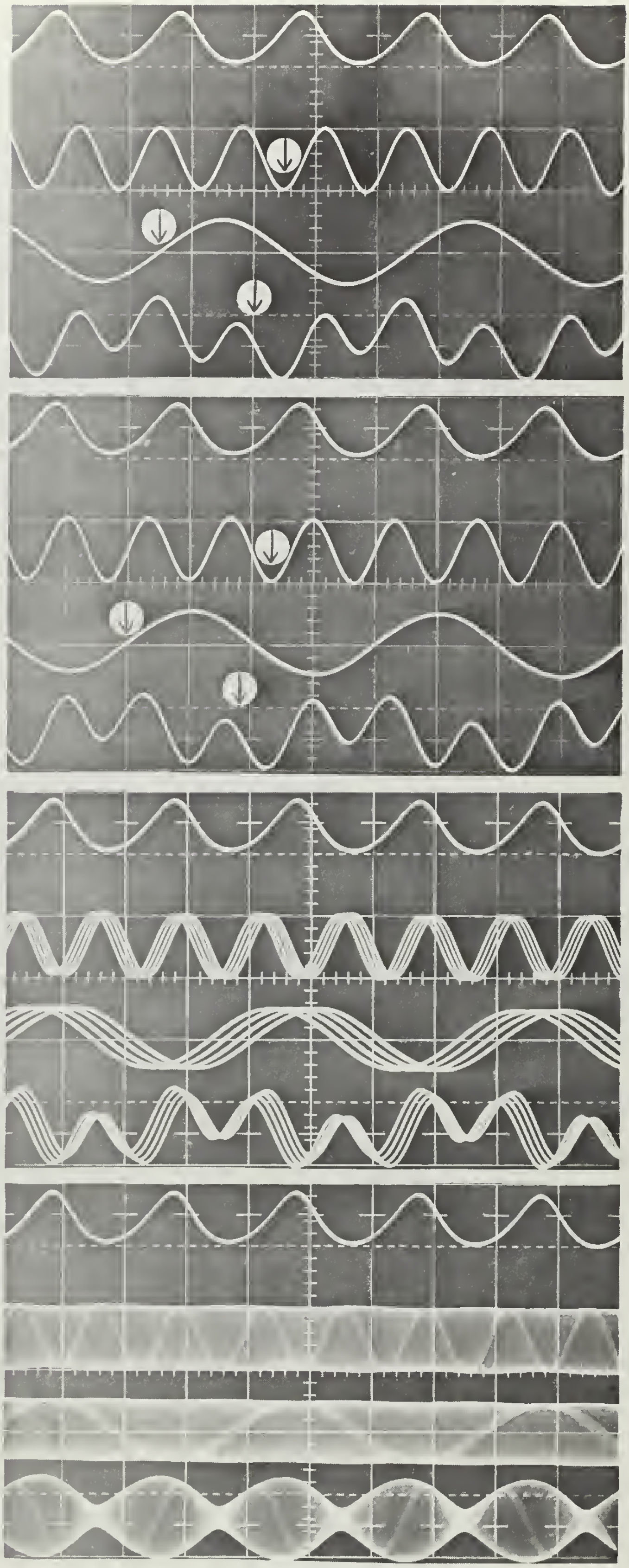


FIG. 14. (continued).

The drift of each of the sinusoidal waveforms is such that precisely $2\pi\delta$ radians of each sinusoid move past a fixed point in one second, but since the wavelength of $p_{12}(t)$ is one third as long as that of $p_{11}(t)$, the apparent <u>linear</u> motion of $p_{12}(t)$ is one third as fast as that of $p_{11}(t)$. This can be seen from the relative progress of the arrowheads in Figs. 14b - 14f.

The behavior of $p_1(t)$ (the 4^{th} trace in Figs. 14b through 14h) is explained by recalling that in Eq. (22), $p_1(t)$ was written as the product of an envelope function, $E_1(t)$, and a carrier term, $\sin [2\pi(1000) - \delta]t$. $E_1(t)$ is not a function of δ and is stationary as shown by Fig. 14h. The carrier term, however, is not stationary. It has a wavelength one-half that of $p_{11}(t)$ and moves half as fast as $p_{11}(t)$.

A result of equal importance to the fact that $p_1(t)$ moves under mistuning is the fact that the reference waveform, $e_1(t)$, remains stationary as the frequency of the transmitter changed. In these photographs, the oscilloscope was triggered from the message function voltage applied at the transmitter. Since the trace of $e_1(t)$ remains perfectly synchronized it could just as well be used for the trigger signal as originally proposed.

C. AURAL-VISUAL DISPLAY OF VOWEL SOUNDS

It is difficult to describe in words or to demonstrate with still photographs the dynamic system display presented to an operator tuning a SSB receiver. Nevertheless, those who have seen the display have readily grasped the significant visual cues which lead to correct tuning. The key apparently lies in the ability of a human operator to visually detect a pattern or form in a rapidly changing display.

When viewed over a long period of time, an amplitude versus time oscillogram of human speech appears to be noiselike. On the other hand, there are portions of a word or word sequences in which the sound exhibits quasi-periodic behavior for a significant number of vibrations. When this occurs, an appropriately triggered oscilloscope traces very nearly the same pattern for a number of sweeps. For example, the photograph in Fig. 15a is a 1/25 second record of several cycles of the waveform of the long "o" vowel sound in "joe". The vowel displayed in this figure is spoken with a fundamental frequency of about 120 Hz, but the persistence of the oscilloscope phosphor permits photographing the several residual traces present at the time the shutter opened.

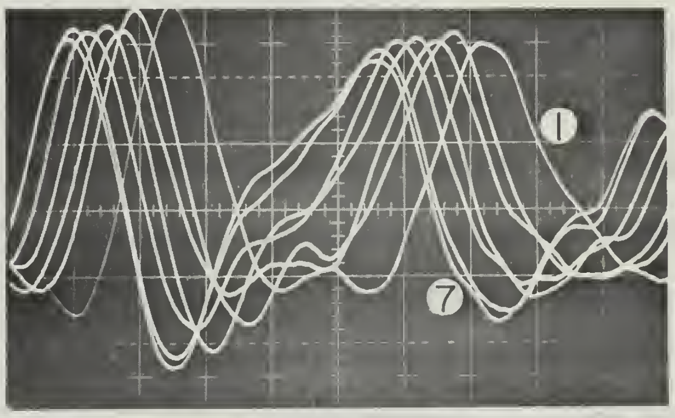
It is clear in Fig. 15a that the waveform changes only slightly from sweep to sweep and a nearly stationary pattern is observed. When a small tuning error is introduced, the traces no longer overlap. Instead the traces appear in sequence, as shown in Fig. 15b, with each successive trace appearing to the left of its predecessor in this particular case. This produces a stroboscopic illusion of motion. These strobes of apparent motion do not appear continuously. Rather, they coincide with strong or emphatic vowel sounds.

When the tuning error is larger than about 30 Hz, the lateral spacing between traces in a stroboscopic burst become large enough that the illusion of motion fails. For this reason, the aural tuning step is necessary to reduce tuning error to a value small enough to facilitate visual tuning.

D. EXPERIMENTAL ACCURACY

To obtain an estimate of the accuracy obtainable with the AVM and its comparative improvement over tuning with aural information alone,

a. Receiver and transmitter are phase locked on precisely the same frequency.



b. Receiver is tuned 6 Hz below the transmitter frequency (-6.0 Hz error). Trace labeled "1" is the earliest trace. The trace labeled "7" is the latest trace.

FIG. 15. VISUAL DISPLAY OF SUSTAINED SPEECH VOWEL SOUND SHOWING EFFECTS OF EXACT AND INEXACT TUNING.

a series of observations were made in which volunteer operators were asked to tune a receiver to five closed-circuit SSB signals using the AVM and then to tune the receiver to five signals using aural tuning alone. The root-mean-square error observed in these tests was 0.750 Hz using the AVM and 8.56 Hz using aural tuning. The maximum error observed using the AVM was 2.0 Hz as compared to 20 Hz using the strictly aural technique.

It is not suggested that these results are necessarily indicative of the results which can be consistently obtained in practice with live signals, but they do show the relative improvement which the AVM can provide under favorable operating conditions.

A number of live frequency measurements of USAF MARS (Military Affiliate Radio Service) SSB stations were made. In most cases the aural step and visual step gave consistent results which appeared valid in all respects. In a small number of these observations it was possible, with the cooperation of the station being monitored, to confirm the results by having the transmitting station modulate with a multi-tone harmonic oscillator to reveal the exact suppressed-carrier frequency* [Ref. 8]. The RMS error observed in these measurements is 1.6 Hz.

A few signals were monitored for which the proper characteristic movement of the visual could not be obtained. Although the reasons for these unsuccessful measurements have not yet been investigated, it is believed that these results are associated with certain peculiarities of the transmitters involved or with speech peculiarities of the operators.

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*This technique is described in Appendix C.

Nevertheless, these observations did not result in erroneous measurements because it is evident in such cases that the correct display is not being obtained.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSION

We have shown the Aural-Visual Method to be a relatively simple and reliable method for tuning a SSB receiver to a SSB voice signal having no discernable carrier. The results of this study lead to the following conclusions:

(1) Under favorable conditions of signal-to-noise ratio, the AVM enables a relatively inexperienced operator to consistently tune a SSB receiver with an error of less than 3 Hz.* (Performance under less-than-favorable signal-to-noise ratio conditions has not yet been determined). This error is less than the recommended maximum error for frequency monitoring station specified in I.T.U. - C.C.I.R. standards [Ref. 2, p. 327] and is approximately an order of magnitude more accurate than any method in current general use for tuning monitoring receivers to SSB signals where no residual carrier can be detected.

(2) While sophisticated laboratory instruments and ultrastable receivers were used in this study to verify the inherent capabilities of the AVM, there is no necessary requirement for this caliber of equipment in the realization of a practical monitoring system using the AVM. It is anticipated, therefore, that the AVM can be implemented using virtually any good quality communications receiver. The accuracy attainable in such a case would be determined primarily by the stability and frequency resolution of the receiver used.

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*It is assumed that tuning a SSB receiver to a SSB signal is experimentally equivalent to measuring the frequency of the suppressed carrier. Several methods for determining the exact frequency to which a receiver is tuned are contained in Appendix D.

(3) The primary practical application of the AVM is believed to be in the area of signal monitoring; particularly the area of frequency monitoring.

B. RECOMMENDATIONS

This study has necessarily been of a very preliminary nature. Many questions relating to the application of the AVM to practical communication systems have not been studied methodically. Several areas for further investigation are suggested below.

(1) There is reason to believe that the operation of the AVM may degrade rapidly as the signal-to-noise ratio (SNR) decreases. Also it appears likely that the presence of certain types of interference may severely impair the operation of the AVM by causing false triggering of the visual display. Further study is indicated to determine the effects of less than ideal SNR upon the operation of the AVM and to determine ways to improve the operation of the AVM under these conditions. (For example, low-pass filtering of the reference signal $e(t)$ may be very effective in improving the operation in the presence of atmospheric noise.)

(2) Many SSB transmitters employ signal processing techniques designed to improve communication effectiveness such as audio-frequency clipping, radio-frequency limiting, speech compression, etc. It would be desirable to determine the effects of these processing techniques upon the performance of the AVM.

(3) It was observed that the envelope detector used to obtain the reference signal in this study was not specifically designed or optimized for envelope detection of a SSB signal. Therefore it is suggested that the effectiveness of the AVM can be improved by using an envelope

detector specifically designed for following the envelope excursions of a SSB voice signal. A simplification of the AVM equipment could be realized by designing this detector to operate upon a sample of the intermediate frequency signal from the SSB receiver.

APPENDIX A

R-1051B/URR MODIFICATIONS

The precision tuning and measurement capabilities of the R-1051B/URR receiver used for SSB reception in this study were greatly extended by the addition of minor modifications which permitted the frequency of the receiver to be set and determined very accurately. These modifications are discussed here.

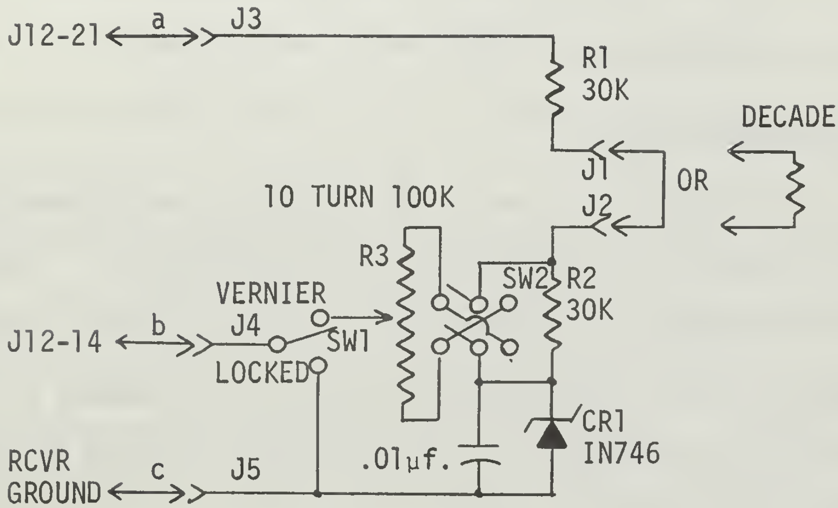
A. REMOTE FINE TUNING UNIT

When the R-1051B/URR is tuned in the incremental, phase-locked mode, the frequency may be changed in 100 Hz steps. In this mode the operating frequency is locked to the phase of a precision standard.

When the receiver is operated in the frequency-vernier mode the 100 CPS OSCILLATOR is unlocked from its reference and is voltage tuned using a one turn potentiometer to provide slightly more than one kHz of frequency change above the frequency selected on the main frequency dials [Ref. 7, p. 4-4A]. The mechanical and electrical resolution of the potentiometer used to tune this VCO is poorer than the oscillator stability. If this potentiometer is replaced with a 10 turn precision potentiometer, it is possible to select receiver frequencies with a resolution on the order of 0.2 Hz.

Fig. A-1 shows the circuit diagram and connection instructions for a simple outboard tuning control providing expanded tuning resolution and increased experimental convenience. This unit replaces similar internal circuitry in the receiver [Ref. 7; Fig. 5-1A, p. 5-14A].

Resistors R1, R2 and R3 form the variable voltage divider used to obtain a tuning voltage between 3.3 volts and 11.5 volts. Reference



Notes: (connection to R-1051B/URR)

1. Remove "freq. control" lead from J12-14 on receiver [Ref. 7; p. 5-14A, Fig. 5-1A].

2. Connect lead "b" (above) to J12-14.

3. Connect lead "a" (above) to J12-21 in addition to the existing lead.

4. Connect lead "c" (above) to a suitable ground tie point in the receiver..

FIG. A-1. CIRCUIT DIAGRAM OF THE REMOTE VERNIER TUNING UNIT.

diode CR1 prevents the selection of a voltage below 3.3 v. Jacks, J1 and J2, are included to permit connection of a resistance decade used to introduce incremental changes useful in some experiments. The switch, SW1, is used to return the receiver to phase-locked operation. SW2 reverses the rotation sense of the control potentiometer.

B. DIGITAL COUNTER READ-OUT

When the R-1051B/URR is used in the frequency vernier mode it is desirable to obtain an instantaneous reading of frequency. Since only the 100 CPS OSCILLATOR is unlocked during vernier operation, the operating frequency can be determined by measuring the frequency of the 100 CPS OSCILLATOR and combining the result with the selected frequency shown on the digital tuning dials.

A probe connected to test point TP3 on the "100 CPS SYNTHESIZER" module [Ref. 7; Fig. 5-15A, p. 5-40A] will sample a voltage the frequency of which varies from 11.000 kHz to 11.999 kHz as the frequency vernier varies the actual operating frequency from that shown on the digital dials to a frequency 0.999 kHz above. The result is that a frequency counter may be connected to TP3 to read the instantaneous vernier frequency. The operating frequency of the receiver is conveniently obtained by subtracting 11.000 kHz from the counter reading and adding the result to the receiver dial reading.

In this manner the receiver frequency can be determined with a resolution less than 1.0 Hz and accuracy determined by the calibration accuracy of the counter standard and the receiver 5 MHz internal standard.

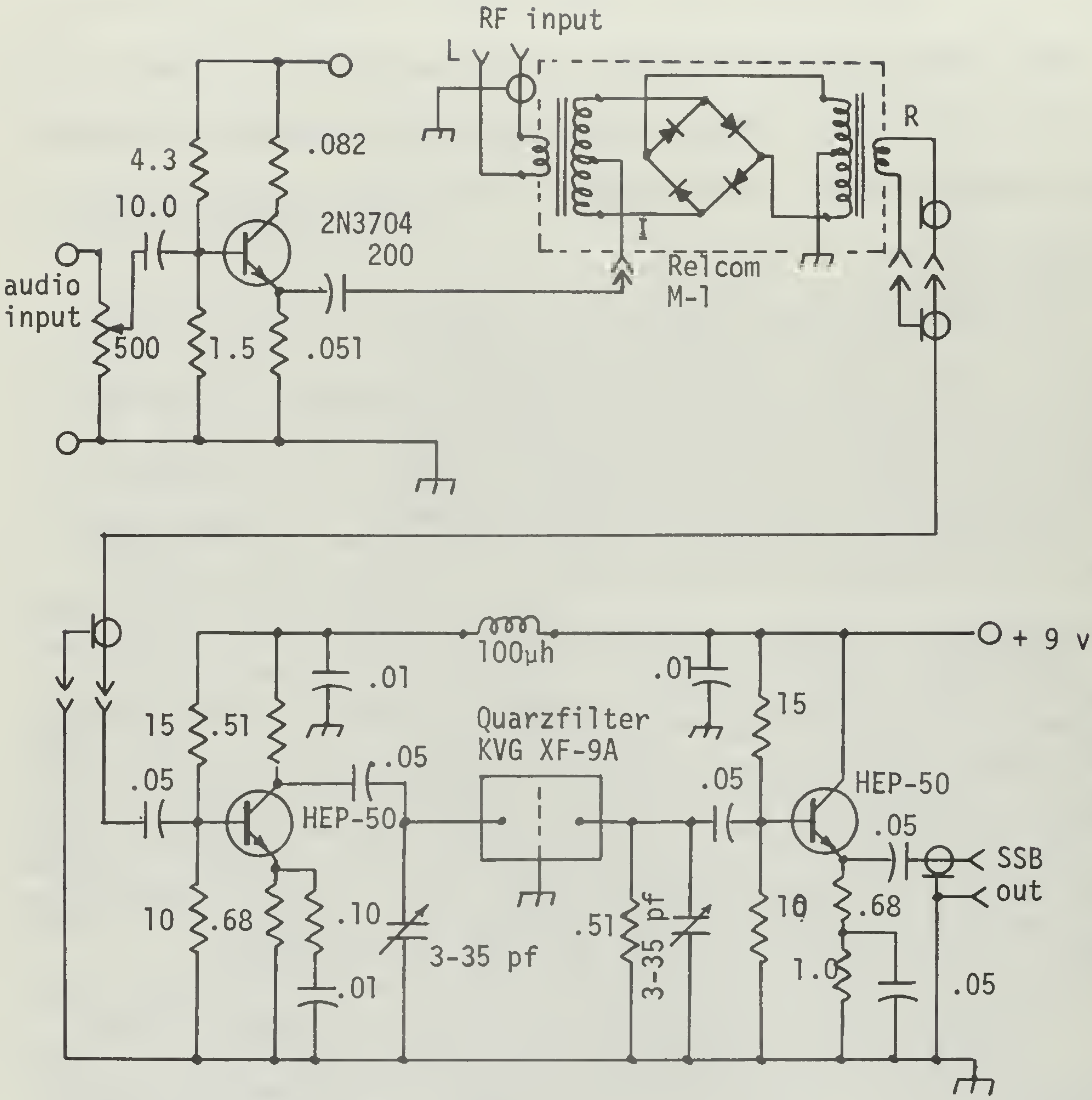
APPENDIX B

A SINGLE-SIDEBAND SUPPRESSED-CARRIER SIGNAL GENERATOR

The circuit diagram of the SSB signal generator used in this study is shown in Fig. B-1. This unit is used to generate either an upper or lower-sideband signal centered about 9.0 MHz depending upon the carrier frequency chosen.

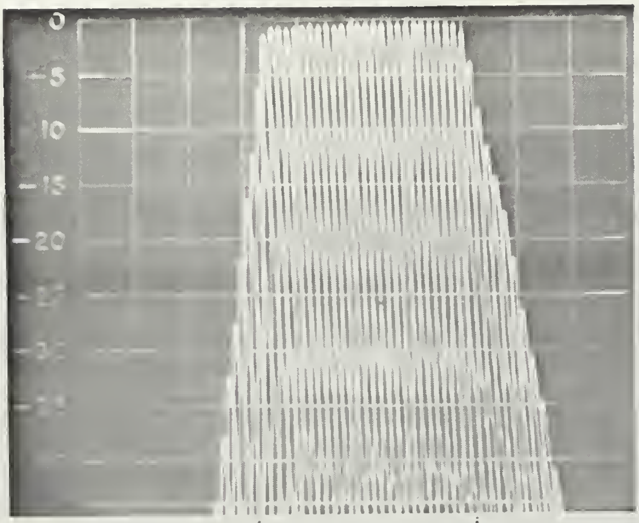
The bandpass characteristic of the sideband filter is shown in Fig. B-2. This plot is made by taking multiple exposure photographs of a spectrum analyzer display as a discrete radio-frequency signal is stepped through the bandpass in 100 Hz increments. A portion of the overall SSB response is shown in Fig. B-3. To obtain this result a carrier having a frequency of 8998.300 kHz is supplied to the balanced modulator and an audio oscillator is used to provide an audio frequency input signal. The spectrum analyzer is tuned to place the carrier frequency at the center of the screen with upper sideband components on the right and lower sideband components on the left. Multiple exposures are made for audio frequencies of 100, 200, 300, 400 and 500 Hz.

The overall carrier suppression is seen to be in excess of 50 db. It can also be seen that for audio modulating frequencies above 300 Hz, the lower sideband component is more than 30 db. down from the upper side frequency.



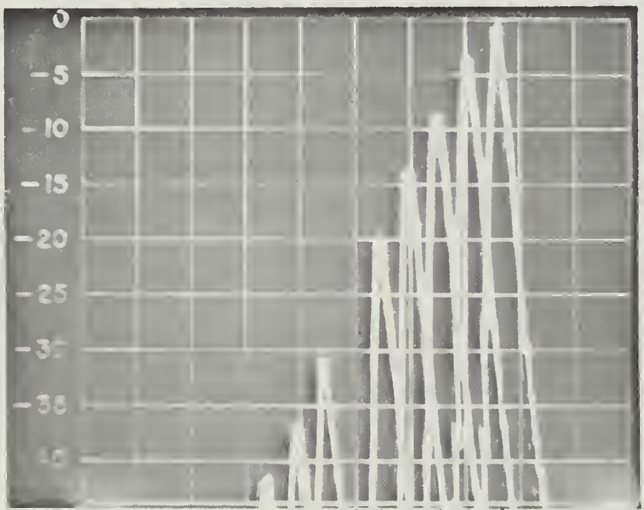
all resistors are kilohms
all capacitors are microfarad unless otherwise indicated

FIG. B-1. SCHEMATIC DIAGRAM OF THE SINGLE-SIDEBAND SUPPRESSED-CARRIER SIGNAL GENERATOR.



8998.600 kHz (6 dB points) 9001.300 kHz

FIG. B-2. BANDPASS CHARACTERISTICS OF SIDEBAND FILTER. Spectrum analyzer display as discrete CW signal is stepped through filter bandpass in 100 Hz increments.



LSF of 300 Hz
LSF of 200 Hz
LSF of 100 Hz
carrier frequency

USF of 500 Hz
USF of 400 Hz
USF of 300 Hz
USF of 200 Hz
USF of 100 Hz

FIG. B-3. SSB GENERATOR FREQUENCY RESPONSE IN THE VICINITY OF THE SUPPRESSED CARRIER FREQUENCY. Carrier suppression and sideband suppression with modulating frequencies from 100 Hz to 500 Hz are shown. LSF means lower side-frequency. USF means upper side-frequency.

APPENDIX C

THE FATTO OSCILLATOR

The FATTO (Frequency Adjusting Two-Tone Oscillator)* technique for tuning a SSB receiver proposed by O'Brien [Ref. 8] and used extensively by SSB stations in the USAF MARS (Military Affiliate Radio Service) Region 6 traffic organization, is a natural ancestor of the AVM [Ref. 9; Ref. 10]. The FATTO method is presented here because it was used for conducting numerous experiments prior to the emergence of the AVM and it was also used to verify the accuracy of on-the-air tests of the AVM.

A detailed theoretical analysis of the FATTO technique would be very similar to that of the AVM. Like the AVM, the FATTO depends upon the tuning of a SSB signal using the a priori knowledge that the demodulated message should have a harmonic spectrum when it is correctly tuned.

The FATTO technique differs from the AVM in that the transmitting station must actively participate in the procedure by transmitting a special signal either upon request or prior arrangement. The requirement that the transmitting station transmit a FATTO signal is somewhat offset by the fact that detection requirements for the FATTO are considerably simpler than those of the AVM.

The tuning technique proceeds in a manner similar to the AVM. The frequency of the transmitting station is first localized by aural voice quality. Fince tuning is accomplished when the transmitting station modulates with a FATTO signal. Correct fine tuning is identified as the

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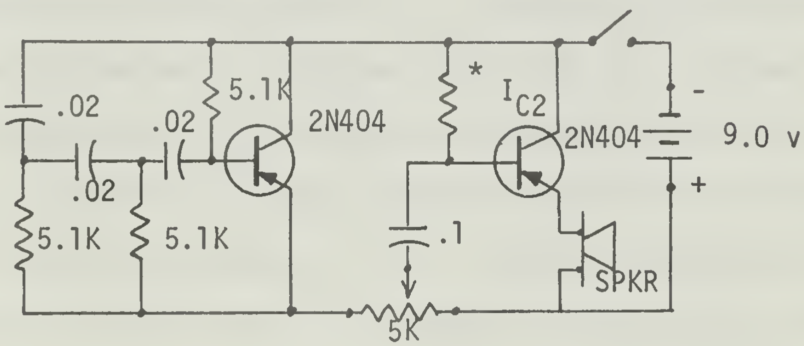
*The FATTO is not actually a two-tone oscillator. It is, rather, a multi-tone oscillator. The term FATTO is used here, however, because this is the name that has come to be identified with the technique by the operators who use it.

condition of receiver tuning which produces a demodulated waveform which does not change shape or form with time.

There are two ways that correct tuning can be observed. The most precise method displays the audio frequency output of the receiver on an internally triggered oscilloscope. Exact tuning is indicated by a stationary pattern.

The second method depends upon the fact that as the shape of a mis-tuned FATTO signal changes slowly with time, the instantaneous peak amplitude changes. This results in an amplitude modulation at the error frequency rate which can be distinguished aurally as an amplitude flutter as correct tuning is approached.

The circuit diagram of the original O'Brien FATTO is shown in Fig. C-1. This consists of a phase-shift oscillator and emitter-follower amplifier driving a loudspeaker. The emitter follower is biased to generate severe harmonic distortion of the oscillator output. These harmonics are used to modulate a transmitter with a multi-tone signal by turning the oscillator on and holding the oscillator loudspeaker close enough to the transmitter microphone to obtain an adequate modulating signal voltage.



* 60K - 300K SELECT FOR $I_{C2} = 20$ ma.

FIG. C-1. SCHEMATIC DIAGRAM OF A FATTO.

APPENDIX D

EXPLICIT DETERMINATION OF RECEIVER FREQUENCY

Throughout this study it has been assumed that tuning a SSB receiver precisely to the frequency of the suppressed carrier is equivalent to determining the carrier frequency. This is true because the correctly tuned receiver stores a replica of the transmitter carrier frequency.

Often, however, it is required to know the carrier frequency explicitly, that is, with more precision than that provided by the receiver dial. The operating frequency of the receiver can be readily computed if the frequency of each oscillator in the receiver (HFO, VFO, BFO, etc.) is measured or known precisely. This method was used in this study to determine the frequency of the R-1051B/URR receiver.

A more general method of determining the exact frequency of a SSB receiver explicitly is known as the offset carrier method. This technique is useful because it permits precise frequency measurement without any internal connections to the receiver.

Since it is normally possible to estimate the frequency of a receiver to within one or two kHz, it is not difficult to adjust the frequency f_g of a CW signal generator to a frequency within the reception bandpass of the receiver. If the signal generator is coupled to the receiver, this results in an audio beat frequency f_b at the receiver output which is the difference between the signal generator frequency f_g and the receiver operating frequency f_d. By measuring the beat frequency f_b and the signal generator frequency f_g, the receiver frequency may be readily computed as

$$f_d = f_g - f_b \quad \text{when} \quad f_g > f_d \tag{D1}$$

or

$$f_d = f_g + f_b \quad \text{when} \quad f_g < f_d \; . \tag{D2}$$

As a matter of convenience it is well to choose either f_g or f_b to be an integral multiple of one kHz. For example, f_g can be set very precisely using harmonic comparison and left fixed. It is then necessary to measure only f_b . On the other hand, it may be preferable to compare the receiver output f_b with a standard 1.0 kHz signal by observing a Lissajous pattern while varying f_g to obtain $f_b = 1.0$ kHz . The choice between these variations of the basic technique depends upon the instrumentation available.

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13. ABSTRACT

A well known problem associated with suppressed-carrier single sideband (SSB) communications is the difficulty of accurately tuning a receiver to the suppressed-carrier frequency of the transmitter if this frequency is not known a priori at the receiver. Although it is possible to tune a receiver to within 20 to 30 Hz of the correct frequency by tuning for the most natural voice timbre (in the case of radio-telephone voice transmissions), this is an unacceptably subjective and inexact method for use in signal and frequency monitoring applications.

This report describes an aural-visual method of tuning a SSB receiver to within about 3 Hz of the suppressed-carrier frequency of a SSB voice signal containing no discernable carrier. This tuning method supplements the familiar aural technique (tuning for most natural voice quality) with a visual oscilloscope display which facilitates an order of magnitude improvement in the accuracy of frequency measurement compared with aural tuning alone.

A theoretical analysis is presented which shows that SSB speech signals contain information sufficient to determine the suppressed-carrier frequency. Also described are experiments which were conducted to indicate the effectiveness of this tuning method in determining the carrier frequency of SSB signals when the SSB message is human speech.

It is suggested that this technique may find application in the domestic and international monitoring services.

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